Good-bye, Willis Carrier

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> At this moment of general diffusion, of international scientific techniques, I propose: only one house for all countries, the house of exact breathing...
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> The Russian house, the Parisian, at Suez or in Buenos Aires, the luxury liner crossing the Equator will be hermetically sealed. In winter it is warm inside, in summer cool, which means that at all times there is clean air inside at exactly 18°.
>
> The house is sealed fast!
>
> — Le Corbusier (1933)

More than half a century has passed since Le Corbusier extolled the virtues of centralized air conditioning systems, yet, the belief persists that these systems produce the most achievable version of "man-made weather." The longevity of this technology has had little to do, however, with its performance or adaptability, but rather with the prodigious timing of its development and introduction. Willis Carrier's and others' work on latent heat control after the turn of the century enabled the rapid maturation of HVAC technology, propelling the industry so far ahead of classical theoretical research that it was effectively isolated from further developments in fluid mechanics and heat transfer. As a result, in spite of increasingly severe problems, the centralized air system has maintained its hegemonic dominion, and the majority of related research in the building industry has sought to fix problems within the technology instead of challenging the paradigm. But the scientific understanding of heat transfer and, particularly, fluid mechanics has progressed so dramatically in the last fifty years that if the precedent of the centralized air system did not already exist, then radically different technologies for thermal control would pervade. How, then, can the industry return to the "fold" to re-integrate the technology with current theoretical understanding? And, who should be conceptualizing the design of the thermal environment?

The centralized air system has remained the choice technology in thermal conditioning because of its ability to control both sensible and latent heat in a space with the same supply air stream. Sensible heat has always been readily easy to control, even in the case of cooling, with latent heat floating as the dependent variable. Willis Carrier's invention of an "Apparatus for Treating Air" in 1903 was a stunning achievement, not for any advancement in direct air cooling, but because it established a strategy for controlling the latent heat content of air. During the development of this apparatus, Carrier's frustration with existing psychrometric data led him to theoretically construct formulae for moisture determination in air. Introduced in 1911 as the "Magna Carta of Psychrometrics," these formulae with their configuration into a psychrometric chart still dictate the methodology for designing HVAC systems.[1] As a result, even though the equipment has evolved significantly over the course of this century, the conceptual strategy for thermal conditioning has not changed.

The use, however, of a single source to control both latent and sensible heats provides, at best, a compromise of the necessary heat transfer actions: latent heat removal is due to the enthalpic sponge created by the sensible heat difference, and sensible heat removal is dependent upon the air-to-air mixing necessary to facilitate the latent heat diffusion. The centralized air system, premised on this compromise between these two modes of heat transfer with very different drivers, will thus perform best when it is operated near the design conditions which will presumably produce perfect mixing. Variations in supply flow rate, temperature or pressure can upset this tenuous balance, particularly if the heat loading of the space is also varying. As such, systems with constant compressor speeds, such as the constant volume system (or CAV), performed most predictably and were the preferred HVAC installation.

From the turn of the century to the early 1970's, electric power use grew 400-fold in the United States. During this supply-side era, if the consumer was willing to pay for power, then the utility companies willingly provided it. Comfort and control were the primary factors influencing environmental systems design, with the result that most HVAC systems were designed with redundant secondary systems so as to cope with the requirements of maintaining comfort levels in spaces with varying load conditions. The Arab Oil Embargo of 1973-1974, and the resulting energy shortages, changed virtually overnight the attitude towards environmental control as suddenly, every building seemed to have an oversized HVAC system. The Variable Air Volume, or VAV, system gained popularity as it essentially maintained the basic integrational structure of the CAV system, but with much less energy usage. Most new buildings designed after the embargo used some type of VAV system, and many constant volume systems in existing systems were retrofitted for VAV operation.

The generous quantities of conditioned air supplied continuously by constant systems were summarily replaced by the penurious meting out of the VAV system. Many of the load variations which had been easily compensated for in constant volume operations, such as thermal mass swings and transient occupant-dependent loads, became nearly insurmountable obstacles. And joining the wide-spread implementation of VAV systems were a host of other energy conservation measures which further increased load variability: peak demand scheduling, duty cycling, economizer operation, occupancy determined lighting and night time shutdowns. Even an oversized CAV system with reheat would be hard pressed to compensate for these variations.

Further compounding the energy usage issues were the inherent problems with indoor air quality resulting from the zealous implementation of energy conscious designs. Buildings were tightened and sealed without any corresponding reassessment of their thermal behavior. As a result, poorly conceived insulation strategies coupled with reduced ventilation contributed to a marked increase in indoor air pollution even though outdoor pollution had been steadily declining. Sick Building Syndrome, Legionnaire's disease, asthma and hypersensitivity pneumonitis are but a few of the illnesses that are directly attributable to poor indoor air quality. And while many of these problems can arise from constant volume systems, the varying ventilation rates produced by VAV systems more readily create the precursor conditions for an unacceptable environment.

Nevertheless, both the HVAC industry and the federal government remained confident that the VAV system, with its already complex thermal interrelationships, could be expected to minimize energy usage, maximize air quality, meet individualized comfort requirements and respond to highly varying loads. Computer simulation and control were deemed the solution for managing these seemingly contradictory demands. In the CAV era, crude whole building approximations that could be manually calculated were often sufficient for determining the ultimate HVAC designs, and simple feedback analog controllers were more than adequate for system operation. But the coupling of the more unstable VAV system with a much wider range of cost saving opportunities demanded not only more sophisticated calculations but also required simulation studies to determine control strategies. In 1973, the U.S. Department of Energy (known then as ERDA), along with the U.S. Post Office and the Department of Defense, began funding the development of computerized energy calculation procedures, eventually releasing two programs to the public domain: BLAST in 1976 and DOE-2 in 1979.[2] These codes, along with many others developed by equipment manufacturers, could perform analyses and simulations where weather data and interior loading mimicked transient conditions for more accurate sizing of equipment than the traditional peak loads analysis. The simulations produced by these codes are presumed to be adequate enough models of the overall thermal behavior that current research is being directed towards using their results actively for system control.

For all of the effort that has been directed towards salvaging the centralized air system, relatively little effort has been applied in the search for alternative means to condition indoor air. A common axiom in the chemical industry is that a well designed process can almost control itself. If this is true for environmental systems as well, then the trouble with the centralized system does not lie with the need to further expand and sophisticate their control schemes. Rather, the question that should be asked is if the system's interactions with the space are properly conceived, and if not, then how should the ideal thermal conditioning system behave?

As Carrier's research and design work was launching the HVAC industry, which then experienced meteoric growth in the United States, related theoretical work in fluid mechanics and heat transfer was at a critical turning point. Unlike most other branches of classical mechanics, fluid mechanics had not developed a theoretical structure that was able to account for generally observable phenomena. As a classical science, theoretical hydrodynamics had evolved from Euler's equations of motion for a frictionless, non-viscous fluid, but it produced results that were contradictory to experimental observations. The empirical science of hydraulics thus emerged to provide a method for solving the practical problems that hydrodynamics was incapable of describing. It was not until 1904, when Ludwig Prandtl introduced the concept of the boundary layer, that these two divergent branches began to be unified.

Boundary layer theory was first applied to problems of drag as an object was moved through a fluid—the drag of a ship or of a turbine blade—and was limited to cases of laminar flow in an incompressible fluid. Eventually, it was extended to turbulent, incompressible flows and finally to compressible flows as it became an essential component in the development of aerodynamics, particularly for the investigation of hypersonic flight. In 1920, G.I. Taylor proposed that the concept of a laminar sublayer could also be applied to problems of heat transfer. Originally, researchers presumed that a thermal boundary layer existed that was analogous to and superimposed on the fluid boundary layer, but later investigations showed that the relationship between these two types of boundary layers was much more complex. As a result, the application of boundary layer theory to heat transfer and to related mass transfer problems of diffusion and evaporation still remains as one of the youngest developing areas of mechanics.

Even though boundary layer theory enabled the analytical description of fluid behavior, the actual solution of the governing equations for predicting behavior was nearly insurmountable for all but the most straightforward problems. Flows of constant velocity near geometrically uniform and symmetric objects were most conducive for effecting a solution, whereas varying flows in crossover regimes demanded a numerically iterative process for approximation. Until the 1970's, empirical collection of data was the preferred method for characterizing complex flows; wind tunnels were used for evaluating aerodynamic behavior, and ship basins up to a mile in length were used for evaluating hydrodynamic behavior. But NASA found that the compressible flow experiments necessary for testing aircraft configurations near the speed of sound were not only prohibitively expensive but also extremely time consuming so they pushed forward the development of computerized numerical analysis. In the late 1970's, the coupling of supercomputers with numerical iteration of the governing equations made Computational Fluid Dynamics (or CFD) an applicable reality, when NASA used it to redesign an experimental aircraft after wind tunnel tests demonstrated unacceptable performance.[3]

Considered the third approach in the philosophical study and development of fluid mechanics, after experimental and theoretical fluid dynamics, computational fluid dynamics is analogous to wind tunnel experimentation while deriving from the governing equations. Essentially, CFD performs numerical experiments, and additionally allows the researcher to investigate those physical aspects of fluid behavior that can not be achieved in a laboratory setting. The advantages of CFD, however, were initially available only to a very limited group of users. Accurate depictions of flows required millions of calculations using time consuming algorithms. The development in 1976 of the Cray-1, the pioneering supercomputer, was in response to NASA's need for faster CFD solutions. The nuclear industry joined the aerospace community, using CFD for modeling jet flows during simulated faults. The expansion of CFD modeling into market driven industries producing turbo-machinery, automobiles and electronics in the mid-1980's led not only to the proliferation of commercially available software but also fostered the refinement of algorithms such that complex problems no longer required a supercomputer. By the end of the 1980's, CFD was finding applications in environmental engineering: weather forecasting, air and water pollution studies, and fire/smoke behavior. It was not until this decade that any significant application of computational fluid dynamics was made to study the thermal behavior of air in buildings.[4]

Why not until now? The fluid mechanics of a room are vastly more complex than those of an airplane, and comparatively speaking, much less consequential. An error made in the design of a wing for an experimental aircraft can cost millions of dollars and possibly take the life of a test pilot, whereas an "error" made in the design of an HVAC distribution system can usually be compensated for *if it is even noticed*. Unlike most other problems in fluid mechanics, in which one or two mechanisms may dominate, building air flow, particularly when centralized air systems are included, is a true mixing pot of behaviors: wide ranging velocities, temperature/density stratifications, transient indoor and outdoor conditions, laminar and turbulent flows, conductive, convective and radiative transfer, buoyant plumes and randomly moving objects (people). This mix of mechanisms has effectively prevented any substantial empirical data collection on building air movement. Unlike single mechanism dominated behavior, such as aircraft or ship drag, which can be scaled down for laboratory or wind tunnel simulation, the multiple mechanisms present in a building environment often produce contradictory scaling parameters, particularly if buoyancy is included, with the result that there is no substantial body of validated experimental data for describing ranges of air flow behavior in buildings. Building air movement had traditionally been described in the most anecdotal of fashions, and experimental measurements have value only for the buildings in which they were collected. And although CFD modeling promised to bring both rigor and expansive data to performance assessment, the lack of any empirical foundation for validation has significantly tempered implementation.

If building air behavior is difficult to characterize empirically, then it is an even more Herculean task to model it for a CFD simulation. Notwithstanding the array of input data establishing the physical definition of the problem, decisions are also required regarding the choice of algorithms, which terms to neglect in the governing equations, the numerical form of the convection operator, the configuration of the mesh, the relaxation method, which turbulence model to use, what thermal mechanisms are significant, and so on. In short, in order to accurately model a problem for CFD analysis, researchers must be as knowledgeable of numerical methods and theoretical fluid mechanics as they are of the specific physical characteristics of the problem. Unfortunately, CFD modelers outside of NASA and other research organizations/universities rarely possess this background.

Concerned by the lack of competent users while CFD usage was burgeoning, the International Energy Agency kicked off a multi-year, multi-country investigation into CFD modeling in 1988. Their initial objectives were ambitious in that they intended to establish the baseline standards for the application of CFD to building analyses. But most interesting was the product they intended to produce: a database of pre-calculated CFD cases on air flow patterns within buildings that would *eliminate* the need for inexperienced engineers to perform CFD modeling or full-scale experimentation. But their objectives were perhaps too ambitious; even though thirteen countries and six independent test labs participated, no significantly applicable direction for users or for researchers was produced, and the general conclusion of the group was that complete validation was an impossible task. Nevertheless, the database was still produced.[5] Several hundred cases were simulated, although all were of the same configuration: a single room office with a window. A decision tree interpolation scheme was set up so that an engineer could input room dimensions, window size, number of occupants and computers, and the HVAC system type with diffuser location, then the database would be searched for the appropriate CFD match. On closer examination, however, these results were no less anecdotal than common-sense observations, and no more accurate than extrapolation of existing data gleaned from diffuser manufacturers. Whether or not design engineers will find a continuing application for this database remains to be seen.

Ambitious as their objectives might have been, the IEA still conceived and directed the most comprehensive investigation into CFD modeling of buildings to date. And most researchers would concur that their methodology was well chosen given the current state-of-the-art in air flow characterization. What went wrong? Is the problem of modeling air behavior in buildings so complex that the methods developed for NASA are not sophisticated enough?

The field of building air behavior is rejoining the science of fluid mechanics after a near century of divergence, but as such, building CFD modelers have grabbed on to CFD methods without embracing their theoretical basis—boundary layer theory. This lack of history in the development of computational fluid dynamics has led to its application as a tool rather than as a philosophical approach. The premise of perfect mixing, which forms the foundation of the centralized air system, still remains as the ideal such that the tendency is to consider that air within a container—a room—is a single entity with multiple behaviors, rather than to conceive that same air as multiple bounded entities of which each is dominated by only one or two behaviors. An analogy might be to consider the attempt to control the multiple behaviors in the perfectly mixed single entity model as being similar to attempting to make an airplane fly by controlling the conditions of the atmosphere rather than of its boundary layer.

Other than the cursory acknowledgment of the boundary layer on a wall, the remaining boundaries in an air space are neglected with the assumption that perfect mixing has actively dissipated them. If air behavior in a space isn't stable then the problem is attributed to the system's inability to produce perfect mixing. The operational boundaries within an airspace, however, are not only highly variable and transient, but can significantly influence the behavior of surrounding air. Numerous intraspatial boundaries can exist within a single space: between laminar and turbulent flow, between isothermal strata, between convective currents and still air, between heat sources and the adjacent air, between zones of different concentrations. Both the location of these boundaries and the rate of heat exchange across them have profound effects on the local air conditions. Instead of eliminating them, by diffusive mixing, what potential may be gained by taking advantage of these boundaries?

But the issue of the appropriate technology returns. It was not through ignorance that the field of HVAC design split away from the science of fluid mechanics, but because an unprecedented technology was developed that dependably delivered the performance that people were demanding. While boundary layer characterization and control was creeping along slowly, the inhabitants of the world were able to enjoy the comforts of 'man-made weather.' And regardless of theoretical compliance, why should one attempt to control a multitude of discrete boundaries when a single system more than adequately met user's needs? Even more significant, there was no technology on the horizon that was capable of providing the type of discrete behavior that would be necessary for controlling air-to-air boundaries. Until now.

Microtechnology has already revolutionized communications and electronic systems due to the rather spectacular electrical properties of silicon. But electronic circuits do nothing more than switch and route electrons, whereas silicon can offer other properties that are spawning perhaps an even more dramatic revolution in mechanical equipment by enabling micromachines that do real mechanical work. Three times as strong as steel, yet with a density less than that of aluminum, silicon also has the near ideal combination of high thermal conductivity but low thermal expansion. More than outperforming traditional mechanical materials, silicon can be machined to micrometer dimensions, can perform electronically and mechanically simultaneously, and already has low-cost mass fabrication facilities. Microelectromechanical systems, or MEMS, are one of the fastest growing commercial technologies of this decade. Sensors and actuators were the among the first MEMS to demonstrate the potential of silicon based micromachines: consider, in particular, the rapid proliferation of MEMS accelerometers that sense sudden deceleration to actuate air bag deployment, and are now included in every new car sold in the United States. Now entering the market are several new sensors, which combine microtechnology with molecular recognition membranes, that may soon allow demand controlled ventilation by carbon dioxide concentration. But while MEMS sensors will bring an accuracy and control to building systems that was never before possible, it is the development of MEMS energy systems that will produce the unprecedented opportunity to integrate scientific theory and technology for the thermal conditioning of buildings.

In 1995, the Department of Energy concluded that the development of MEMS for distributed energy conversion systems in buildings was their highest priority in microtechnology research, thus displacing sensors as the primary focus.[6] Among the benefits they highlighted were: reduced distribution losses and power requirements, improved efficiency due to individualized control, improved fundamental conversion efficiency from microscale processes, improved load efficiency due to the staging of conversion modules, and the elimination of CFC/HCFC refrigerants. Under development now are micro heat-pumps, heat engines, compressors, evaporators, condensers and pumps, all sized with a maximum dimension of 50-1000 microns. Already commercially available are micro-channels and heat pipes for electronic circuit cooling. Of course, stepping up from a circuit to an entire building was until quite recently considered ludicrous. An inherent assumption in fluid mechanics theory is that continuum behavior breaks down at small scales. But advances in imaging have now given confidence that continuum behavior is valid well into the *nanometer* range. As a result, scaling up from a circuit to a building became only an issue of quantity rather than of technical feasibility.

Pacific Northwest Laboratory, who directs the micro-energy project for the Department of Energy, believed that the quantity issue was surmountable, particularly if full advantage was taken of MEMS capabilities to eliminate large centralized systems for smaller distributed installations. In 1994, they projected that if they could build a micro-heat pump that, if connected in series, was able to transfer 1 watt per square centimeter, then a one square meter sheet of heat pumps no thicker than wallpaper could easily heat and cool the typical house.[7] But by early 1996, they had already exceeded their expectations dramatically, and were testing micro-heat pumps that were capable of transferring 25 watts per square centimeter. The technology was clearly achievable; less clear, though, was the system for actually deploying it in a building. PNL has recognized that huge advantages exist for a distributed system versus a centralized system, and so they envision that their micro heat pumps would be distributed throughout building, providing discrete response for localized needs. The distribution stops, however, at the room level. And much of their current focus has been on breaking up the laminar boundary layer of the heat pump sheet so as to facilitate greater air mixing in the room. The near-century old precedent of perfectly mixed air still prevails.

A new technology has arrived at the same time that a new philosophical understanding of fluid mechanics is becoming established. MEMS and CFD complement each other ideally, the latter enabling a means to characterize discrete behavior in fluids, the former providing the ability to act at a discrete level. A breakthrough in the thermal conditioning of buildings should be imminent, yet focus and direction is missing. When a similar convergence of new technology—electromechanical equipment—and scientific understanding—psychrometry—occurred at the turn of the century, Willis Carrier stepped forward and revolutionized the heating and cooling of buildings. Who, today, can take Carrier's place?

For most of this century, the thermal environment has been the responsibility of the HVAC designer, while the architect struggled only to integrate the physical, and static, shell of the conditioning system. What if it was within the architect's power to design the transient environment? To design the way a space feels rather than just how it looks? Would one want the fingertips to be warmer than the nose? Should different zones within a room be of different temperatures to sequentially engage and disengage the body? Could thermal zones take the place of walls? Or would one want to create a thermal shield around the body that moved with the body, but could be activated or deactivated at whim. None of these scenarios are premised on the need for perfect mixing or centralized systems. And all of these scenarios are possible by coupling emerging technology with a more fundamental application of fluid mechanics principles.

NOTES

1. Margaret Ingels, *Willis Haviland Carrier, Father of Air Conditioning* (Garden City: Country Life Press, 1952) p. 41.
2. J. Marx Ayres and Eugene Stamper, "Historical Development of Building Energy Calculations," *ASHRAE Journal* 37/2 (1995) p. 47.
3. The experimental NASA aircraft—HiMAT (Highly Maneuverable Aircraft Technology)—was designed to test concepts for the next generation of fighter planes. Wind tunnel tests showed that it would have unacceptable drag near Mach 1. Continuing to redesign it and test in wind tunnels would have cost $150,000 and significantly delayed the project. Instead, CFD was used to redesign the wing at a cost of $6000. John D. Anderson, Jr., *Computational Fluid Dynamics* (New York: McGraw-Hill, Inc., 1995) p. 3.
4. By significant application, I am referring to the use of CFD to impact building system design or performance parameters at a level commensurate to its application in other industries. Researchers, nevertheless, have been exploring the potential of CFD to predict air movement in buildings since 1974. J.J. McGuirk and G.E. Whittle, "Calculation of buoyant air movement in buildings - proposals for a numerical benchmark test case," in The Institution of Mechanical Engineers, *Computational fluid dynamics* (London: Mechanical Engineering Publications Limited, 1991) p. 14.
5. Q. Chen, A. Moser and P. Suter, *A Database for Assessing Indoor Airflow, Air Quality, and Draught Risk* (Zurich: Institut fur Energietechnik, 1992)
6. Pacific Northwest Laboratory, *The Potential for Microtechnology Applications in Energy Systems - Results of an Expert Workshop* (U.S. Department of Energy Publication PNL-10478, 1995) pp. 4.1, C.2-C.3.
7. Robert S. Wegeng and M. Kevin Drost, "Developing new miniature energy systems," *Mechanical Engineering* 116/9 (1994) p. 85.